Asymmetric neutrino emision and formation of rapidly moving pulsars

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Abstract

The neutron star formation during the collapse with the strong magnetic field may lead to a mirror symmetry violation and formation of an asymmetric magnetic field. Dependence of the week interaction cross-section on the magnetic field strength lead to the asymmetric neutrino flux and formation of rapidly mooving pulsars due to the recoil action as well as rapidly moving black holes.

1. Introduction

Existence of the pulsars moving with the velocities up to 500 km/s (Harrison, Lyne and Anderson, 1991) is a big challenge to the theory of the neutron star formation in the spherically symmetrical collapse. Collapse of the rotating star with an axial symmetry make no changes and the consideration of the Blaauw effect during the formation of pulsars in the binaries cannot produce such a high speeds. The most plausible explanation for the birth of rapidly mooving pulsars seems to be a suggestion of the kick at the birth from the asymmetric explosion (Shklovskii, 1970, see also Radhakrishnan, 1991). Here the estimations are made for the strength of the kick, produced by the asymmetric neutrino emission during the collapse. Chugay (1984) and Dorofeev, Rodionov and Ternov (1985) tried to produce the asymmetric neutrino pulse due to the action of the strong magnetic field, which make the electrons to be polarized. It leads to the mirror asymmetric neutrino emission due to the P symmetry violation in the week interaction Lagrangian. As was shown by Bisnovatyi-Kogan (1989), the strength of the poloidal magnetic field needed for the explanation of the visible velocities is much larger, then the fields, observed in theese pulsars.

The asymmetry of the neutrino pulse, considered here is produced by the asymmetry of the field distribution, formed during the collapse and differential rotation (Bisnovatyi-Kogan and Moiseenko, 1992). Qualitative picture of the neutrino pulse asymmetry due to the dependence of the neutrino cross-section on the magnetic field strength was considered by Bisnovatyi-Kogan (1991). Here the quantitative estimations are presented.

2. Formation of the asymmetric magnetic field distribution

In order to obtain the mirror asymmetric magnetic field distribution let us consider a rotating presupernova star with the dipole poloidal and symmetric toroidal field. Collapse of such star after the loss of stability lead to the formation of the rapidly and differentially rotating neutron star. The field amplification during the differential rotation lead to the

formation of the additional toroidal field from the poloidal one. The toroidal field, made from the dipole poloidal by twisting of the field lines is antisymmetric relative to the symmetry plane. The sum of the initial symmetric with the induced antisymmetric toroidal fields has no plane symmetry and the field in one hemisphere is larger then in another one. Such symmetry violation happens always when the star begins to rotate differentially and posesses toroidal and poloidal fields with the different symmetry properties (dipole poloidal and symmetric toroidal; or quadrupole poloidal with antisymmetric toroidal; etc).

In the absence of the dissipative processes with the perfect magnetic field freezing the neutron star returns to the state of rigid rotation loosing the induced toroidal field and restoring mirror symmetry of the matter distribution. In the presence of the field dissipation the rigidly rotating star returns to the rigid rotation having an asymmetric toroidal field and an asymmetry of the matter distribution. The formation of the asymmetric toroidal field distribution may be followed by the asymmetric magnetorotational explosion, producing the neutron star recoil and the rapidly mooving star (Bisnovatyi-Kogan, 1970; Ardelyan et. al.,1979; Bisnovatyi-Kogan, Moiseenko,1992). Even in the case, when the magnetorotational explosion is not effective, the neutron star accelleration may happen due to the dependence of the cross-section of the week interactions on the magnetic field.

Influence of the magnetic field on the processes of week interaction was studied well for the process of the neutron decay (O'Connel, Matese,1969). The influence begins, when the characteristic energy of the electron on the Landau level with the Larmor rotation $\frac{\hbar e B}{m_e c}$ becomes of the order of the energy of the decay, which for the neutron decay is of the order of $m_e c^2$. The equality of these energies determines the critical magnetic field

$$B_c = \frac{m_e^2 c^3}{e\hbar} = 4.4 \times 10^{13}\text{Gs} \tag{1}$$

The probability of the neutron decay W_n in the strong magnetic field without the matter is

$$W_n = W_0[1 + 0.17(B/B_c)^2 + ...] \quad \text{at} \quad B \ll B_c$$
$$W_n = 0.77 W_0(B/B_c) \quad \text{at} \quad B \gg B_c \tag{2}$$

The formulas (2) may be easily generalized for the neutron decay and the electron capture in the presence of matter with Fermi distribution, what needs only changes of the phase volume of the integration. For the fully degenerate electrons the integration over the phase volume may be done analitically (see, e.g. Shulman,1977). In the fully degenerate case the smooth dependence of the decay or capture probabilities on the field strength is accompanied by the jumps of the derivatives when the difference between the energy of the decay and the Fermi energy of the electrones connected with the motion along the maghetic field crosses the energy of the corresponding Landau level. The neutrino emissivity from the synchrotron and $e^+ e^-$ annihilation processes in the nonrelativistic limit were studied by Kaminker et.al. (1991).

After the collapse of the rapidly rotating star the new forming neutron star rotates with the period P about 1 ms, corresponding to the critical rotational velocity. Differential rotation leads to the linear amplification of the toroidal field, according to the approximate law

$$B_\phi = B_{\phi 0} + B_p(t/P) \tag{3}$$

Numerical calculations of the spherically symmetrical collapse gave (Nadjozhin, 1978) several tens of seconds for the time of the neutrino emission. This time may even increase with an account of the rotation. During 20 s the induced toroidal magnetic field will become equal to $2 \times 10^4 B_p$, corresponding to $10^{15} \div 10^{17}$ Gs for $B_p = 10^{11} \div 10^{13}$ Gs, observed in the pulsars. Adopting the initial toroidal field equal to $B_{\phi 0} = (10 \div 10^3) B_p = 10^{12} \div 10^{16}$, we may start the estimation of the asymmetry of the neutrino pulse produced by the anisotropic neutrino emission. It is easy to see, that for symmetric $B_{\phi,0}$ and dipole poloidal field the difference ΔB_ϕ between the magnetic fields absolute values in two hemispheres increases, until it reaches the value $2B_{\phi 0}$. It remains constant later, while the relative difference

$$\delta_B = \frac{\Delta B_\phi}{B_{\phi+} + B_{\phi-}}$$

decreases.

3. Neutrino heat conductivity and energy losses

The main neutrino flux is formed in the region where the mean free path of the neutrino is less then the stellar radius. The neutrino energy flux, H_ν connected with the temperature gradient may be written as (Imshennik, Nadjozhin, 1972)

$$H_\nu = -\frac{7}{8} \frac{4acT^3}{3} l_T \frac{\partial T}{\partial r} \qquad (4)$$

Here was neglected the part of the heat flux, connected with the gradient of the lepton charge. In order to estimate the neutrino flux distribution over the surface of the star we consider for simplicity a set of spherically symmetrical stars with different neutrino opacity distributions and the same central temperature. The value l_T having a sence of the neutrino mean free path is connected with the neutrino opacity κ_ν as

$$\kappa_\nu = 1/(l_T \rho) \qquad (5)$$

Calculations of the spherically symmetrical collapse (Nadjozhin, 1978) have shown, that during the phase of the main neutrino emission the hot neutron star consists of the quasiuniform quasiisothermal core with the temperature T_i, the mass of which increases with the time, and the region between the neutrinosphere and the isothermal core, where the temperature smoothly decreases in about 10 times and behaviour of density, which finally drops about 6 times is nonmonotoneous. In this region, containing about one half of the neutron star mass, neutrino flux is forming. We suggest for sumplicity in this region the power dependences for the temperature

$$T = T_i \left(\frac{r_i}{r} \right)^m \qquad (6)$$

and for l_T

$$l_T = \frac{1}{\kappa \rho} = l_{Ti} \left(\frac{r}{r_i} \right)^n \qquad (7)$$

The neutrinosphere with the radius r_ν is determined approximately by the relation

$$\int_{r_\nu}^\infty \kappa_\nu \rho dr = \int_{r_\nu}^\infty \frac{dr}{l_T} = 1 \tag{8}$$

Using the distribution (7) outside the neutrinosphere we get from (8) the relation

$$r_\nu = r_i \left(\frac{r_i}{(n-1)l_{Ti}} \right)^{\frac{1}{n-1}} \tag{9}$$

From (4)-(7), using (9) we get the temperature of the neutrinosphere T_ν and the heat flux on this level H_ν, which outside the neutrinosphere is approximately $\sim r^{-2}$, corresponding to the constant neutrino luminosity L_ν

$$T_\nu = T_i \left(\frac{(n-1)l_{Ti}}{r_i} \right)^{\frac{m}{n-1}} \tag{10}$$

$$L_\nu = 4\pi r_\nu^2 H_\nu = \frac{7}{8} m \frac{16\pi a c T_i^4}{3} (n-1)^{\frac{4m-n+1}{n-1}} r_i^2 \left(\frac{l_{Ti}}{r_i} \right)^{\frac{4m-2}{n-1}} \tag{11}$$

In order to estimate the anisotropy of the neutrino flux we compare two stars with the same radius and temperature of the core r_i and T_i and different opacities (different l_{Ti}). Consider for simplicity a star where l_{Ti} is different and constant in two hemispheres, the laws (6) and (7) are the same and each hemisphere radiate independently with the luminosities, equal to one half of (11) with different l_{Ti}. The anisotropy of the flux

$$\delta_L = \frac{L_+ - L_-}{L_+ + L_-} \tag{12}$$

with L_+ and L_- as luminosities in the different hemispheres, may be calculated, using (11). For small difference between hemispheres we get from (11)

$$\delta_L = \frac{\Delta L}{L} = \frac{4m-2}{n-1} \frac{\Delta l_{Ti}}{l_{Ti}} \tag{13}$$

It is clear from (10), that neutrinosphere exist only at $n > 1$. It follows from (11), that when $m = \frac{1}{2}$ the neutrino fluxes in both hemispheres are equal because smaller opacity and larger neutrinosphere temperature T_ν from (10) is compensated by smaller neutrinosphere radius r_ν from (9), so that the luminosity, determined by the product $T_\nu^4 r_\nu^2 \sim T_\nu^4 r_\nu l_{T\nu}$ is constant. For $m > \frac{1}{2}$ the larger l_{Ti} corresponds to the larger luminosity, what means the total excess of the more energetic neutrino, and the opposite situation happens for $m < \frac{1}{2}$. Let us emphasize that this conclusion is valid only for the same power dependences (6) and (7) for T and l_T with different values of l_{Ti} at the boundary of the isothermal core. It is not possible to apply this conclusion directly for the different opacity laws, like in the case of the stellar neutrino luminosity in different neutrino sorts (electron, muon and tau).

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4. Neutron star acceleration by anisotropic neutrino pulse.

The equation of motion of the neutron star with the mass M_n radiating the anisotropic neutrino flux is written as

$$M_n \frac{dv_n}{dt} = \frac{1}{c} \int_0^\pi L_\nu(t, \theta) \cos\theta d\theta \tag{14}$$

The total neutrino luminosity

$$L_\nu(t) = \int_0^\pi L_\nu(t, \theta) d\theta \tag{15}$$

may be taken from the spherically symmetrical calculations of Nadjozhin (1978) or Mayle et.al (1987). Consider for simplicity, that the neutrino fluxes in upper L_+ and lower L_- hemispheres are constant over θ. Then (14),(15) may be written as

$$M_n \frac{dv_n}{dt} = \frac{L_+ - L_-}{c} \tag{16}$$

$$L_+ + L_- = \frac{2}{\pi} L_\nu(t) \tag{17}$$

For the power distributions (9),(10) it follows from (11) the dependences

$$L_\pm = A l_{Ti\pm}^{\frac{4m-2}{n-1}} \tag{18}$$

where $l_{Ti\pm}$ are the average values of I_{Ti} in two hemispheres. In general l_{Ti} is determined by different neutrino processes and depends on B.

As an example consider the dependence on B in the form (2). Making interpolation between two asimptotics we get dependence

$$l_{Ti\pm} \sim \frac{1}{W} = l_{T0} \frac{1 + \left(\frac{B}{B_c}\right)^3}{1 + 0.17\left(\frac{B}{B_c}\right)^2 + 0.77\left(\frac{B}{B_c}\right)^4} \tag{19}$$

The time dependence of the average value of B in each hemisphere may be found from (3), taking average values of $B_{\phi 0\pm}$ and average values of $B_{p\pm}$, so that

$$B_{p+} = -B_{p-}, \quad B_{\phi 0+} = B\phi 0- \tag{20}$$

The values of $l_{Ti\pm}$ in each hemisphere may be written as

$$L_\pm = A l_{T0}^{\frac{4m-2}{n-1}} F_\pm = D(t) F_\pm \tag{21}$$

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where $F\pm$ as a function of B may be found from the comparison with (18), (19) and B as a function of time is taken from (3) with account of (20). From (17),(21) we get

$$D(t) = \frac{2L_\nu(t)}{\pi(F_+ + F_-)} \tag{22}$$

The equation (16) with account of (21),(22) may be finaly written as

$$M_n\frac{dv_n}{dt} = \frac{2}{\pi}\frac{L_\nu}{c}\frac{F_- - F_+}{F_- + F_+} \tag{23}$$

where the time dependence of L_ν is taken from the spherically symmetrical calculations of the collapse and nondimentional time functions $F\pm$ are determined by the structure of the neutron star above the isothermal core and the average time dependence of B_ϕ in two hemispheres.

5. Numerical estimations

Consider for simplicity the distributions (6),(7) with

$$\frac{4m - 2}{n - 1} = 1 \tag{24}$$

The main acceleration of the neutron star occures when $B \gg B_c$, so the functions $F_\pm$ reduce to

$$F_\pm = \frac{B_c}{0.77B_\pm} \tag{25}$$

and the equation of motion (23) may be written as

$$M_n\frac{dv_n}{dt} = \frac{2}{\pi}\frac{L_\nu}{c}\frac{|B_+| - |B_-|}{|B_+| + |B_-|} \tag{26}$$

For linear functions

$$B_\pm \equiv B_{\phi\pm} = a \pm bt \tag{27}$$

$$a = B_{\phi 0}, b = \frac{|B_p|}{P}$$

with a and b determining by (3),(20). Take constant L_ν

$$L_\nu = \frac{0.1M_nc^2}{20s} \tag{28}$$

With these simplifications the final velocity of the neutron star v_{nf} as a result of the solution of (26) is written in the form

$$v_{nf} = \frac{2}{\pi}\frac{L_\nu}{M_nc}\frac{PB_{\phi 0}}{|B_p|}\left(0.5 + \ln\left(\frac{20\,s}{P}\frac{|B_p|}{B_{\phi 0}}\right)\right) \tag{29}$$

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For $P = 10^{-3} s$ and L_ν from (28) we obtain from (29)

$$v_{nf} = \frac{2}{\pi} \frac{c}{10} \frac{P}{20\,s} x(0.5 + \ln(\frac{20\,s}{P}\frac{1}{x})) \approx 1\frac{km}{s} x(0.5 + \ln \frac{2 \times 10^4}{x}) \tag{30}$$

For the value $x = \frac{B_{\phi 0}}{|B_p|}$ between 20 and 10^3, we have v_{nf} between 140 and 3000 km/s, what can explain the most rapidly mooving pulsars. The formula (30) may be applied when $B_{\phi 0} \gg B_c$ and $x \gg 1$.

For nonlinear dependence in (18) the analitical estimation of v_n may be done, when the main acceleration happens when

$$bt \gg a \tag{30}$$

in (27). In the same conditions $B_\pm \gg B_c$ we have

$$F_\pm = \left(\frac{B_c}{0.77 B_\pm} \right)^{\frac{4m-2}{n-1}} \tag{31}$$

Making expansion in (31), using (27),(30), we obtain from (23)

$$M_n \frac{dv_n}{dt} = \frac{2}{\pi} \frac{L_\nu}{c} \frac{4m-2}{n-1} x \frac{P}{t} \tag{32}$$

Integration of (32) gives the result which differs from (30) approxomately only by multiplicator $(4m-2)/(n-1)$

$$v_{nf} = \frac{2}{\pi} \frac{c}{10} \frac{P}{20\,s} x \frac{4m-2}{n-1} \ln(\frac{20\,s}{P}\frac{1}{x}) \approx 1\frac{km}{s} \frac{4m-2}{n-1} x \ln \frac{2 \times 10^4}{x} \tag{33}$$

Acceleration of the collapsing star by anisotripic neutrino emission may be done even when the star does not stop on the stage of the neutron star and collapses to the black hole. We may expect black holes of stellar origin moving with rapid velocities, like radiopulsars. It means, that they may be situated much higher over the galactic disk, then their progenitor - very massive stars.

6. Conclusion.

The results, obtained above have shown, that the anisotropy of the neutrino pulse, produced by the mirror asymmetric magnetic field distribution may explain the observed high velocities of radiopulsars for realistic magnetic field strengthes. This mechanism of acceleration acts in all cases of anisotropic neutrino emission, including the case of the formation of black hole. It means, that black holes could be found on the distance from the galactic plane much larger, then the thickness of the Galactic disc, containing very massive stars.

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